12/4-4-94 JS(1)

UCRL-ID-116360

A STUDY OF NEAR-SURFACE AND UNDERWATER EXPLOSIONS BY COMPUTER SIMULATIONS

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February 1994

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

A Study of Near-Surface and Underwater Explosions by Computer Simulations

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Abstract

Computer simulations were made for 13 near-surface and underwater explosions from generic 1-kt and 10-kt sources. The objective is to calculate energy coupling to the water and to understand conditions that drive signals into the ocean sound channel. The simulation used the CALE computer program, which was previously validated using the WIGWAM test data. A 1-kt underwater explosion achieves its maximum coupling at about 20 m DOB, and the downward kinetic energy is less than 15% of the yield. As the source is lifted above the surface, the coupling efficiency decreases dramatically. A comparison of underwater explosion simulations for the two different yields confirmed that hydrodynamic dimensions scale by the cube root of the yield.

Introduction

This report describes a study of energy coupling in the ocean for near surface and underwater explosions of 1 kt and 10 kt. The objective of this study is to develop accurate descriptions of the source region that ultimately drives wave propagation in the SOFAR (Sound Fixing And Ranging) channel. The long-distance transport of low-frequency signals in the SOFAR channel is a remarkable feature of ocean acoustics.[1] The channel is created by the minimum in the underwater sound speed at varying depths (typically about 1 km). Snell's law says that rays representing a propagating wave bend toward water of lower sound speed.[2] The existence of a vertical minimum in sound speed and Snell's law cause the rays to oscillate about the sound channel axis, forming approximately sinusoidal curves with wavelengths on the order of many kilometers.[2]

Our goal is to make a quantitative study, under various conditions, of the correlation between the initial source description and the final acoustical signatures received at a great distance . The study is performed entirely by computer simulations. This report is the first of a series to be published as the investigation progresses.

In a previous report,[3] we described the computer simulations of the WIGWAM underwater experiment[4,5] and particularly the calculations of the signals that were measured by the gauges suspended in the water. Agreement of the calculations with the measurements demonstrated the validity of our simulation technique using a 2-D hydrodynamic computer program, CALE.[6,7] Applying CALE (an Arbitrary Lagrange Eulerian code written in C language) in this study, we investigated the energy coupling of a 1-kt source placed at water depths of 0, 5, 10, 20, and 100 m, and at heights above the water of 10, 20, and 43 m. Similar calculations were run for a 10-kt source placed at depths of 0, 21.5, 43, and 215 m, and at a height of 43 m. These positions for the 10-kt source were determined by cube-root yield scaling so that a comparison of the two sources can be made at equal scaled depths or heights. We included the effects of gravity on the system kinetics via a pressure over-burden in the ocean water.

The calculations were run until the signal peak pressures fell below 200 bars. In subsequent studies, the output from a CALE calculation will be linked at this pressure to a hydro-acoustics computer program, NPE Code[8,9] (Nonlinear Progressive Wave-equation Code) to analyze long distance propagation of acoustic signals. When signal peak pressures fall below one-tenth of the bulk modulus of water (22.4 kbars), the weak shock assumption in the NPE Code provides fairly accurate answers. However, we ran all the CALE calculations to the point where peak pressures were below one-hundredth of the bulk modulus to make certain that the weak shock model in the NPE code will be accurate.

Computer Simulations

The CALE mesh can be run in a self-mending mode so that it performs Eulerian-like mass advection whenever its Lagrangian mesh is strained by an excessive deformation. This facilitates simulations of dynamic events that involve substantial material distortion. Also, CALE can be operated in either the pure Eulerian mode or the pure Lagrangian mode, and, in addition, the operational mode can be changed during a simulation run.

The two-dimensional simulations were run with a polar mesh. A partial schematic for a simulation of a 1-kt underwater explosion is shown in Fig. 1. The energy source is modeled by an iron gas bubble with a density of 0.5 gm/cc and radius of 1 m. The mass of the iron bubble is 2100 kg in which the 1-kt energy is uniformly distributed. The polar coordinates are centered in the iron bubble. The surrounding material is water with a density of 1.0 gm/cc or air with a density of 1.3×10^{-3} gm/cc, depending on the location of the explosion. The horizontal line in Fig. 1 defines the air–water interface. Zones that the line cuts across are mixed zones containing air and water.

The angular resolution of the polar mesh is 5°. There are five equal radial zones in the iron bubble, and the radial zones in the water increase geometrically from 0.1 m at the iron–water interface to 0.5 m and then maintain an equal zoning of 0.5 m. But for near-surface explosions, the radial zones in the air increase geometrically from 0.1 m at the iron–air interface to 0.5 m, and then they are geometrically reduced to 0.1 m at the air–water interface. We found that fine zoning at the air–water interface was needed to calculate accurately the entry of the air blast into the water.

The 10-kt source is modeled by an iron gas bubble with a density of 0.5 gm/cc and radius of 2.15 m. The mass of iron is 21,000 kg in which the total yield is uniformly distributed. There are 10 equal radial zones in the bubble, and the zoning of the other materials is like that for the 1-kt source.

H-Division at LLNL developed the equation-of-state for iron,[10] for air[11] and for water,[12] and all are in tabular form with pressure as a function of density and temperature. The gravitational overburden was calculated only in the water. The vertical pressure gradient was ignored in the atmosphere. In order to minimize numerical noise behind the wave front, a carefully adjusted scalar Q (artificial viscosity) was used. This technique is described in the WIGWAM report.[3]

Results and Discussion

For shallow underwater explosions, when the upward wave reaches the water surface, the surface is set strongly in motion. The returning rarefaction wave communicates the surface motion to the bubble, and the bubble rises. The expanding bubble breaks through the surface, and the simulation strains the nearly Lagrangian-like ALE-mesh. We found that for 1-kt explosions at 5 m and 10 m DOBs we could not complete the simulations accurately with the standard ALE mode; thus we switched to the pure Eulerian mode. Figure 2 shows the bubble for 10 m DOB at 150 msec; more than a half of the bubble has risen above the water surface. The standard ALE mode could not have carried the computation this far.

The deeper explosions (at 20 m and 100 m) caused few difficulties for the ALE-mesh. Figure 3 shows the state of the bubble for 20 m DOB at 150 msec. The bubble boundary exhibits Lagrangian zoning which can better resolve the initiation of the shock wave. We encountered similar difficulties for the 10-kt explosions: the deeper explosions at 43 m and 215 m DOBs were simulated with a Lagrangian-like ALE mesh while the shallow explosion at 21.5 m could be computed only with an Eulerian mesh. Likewise the near surface explosions were best simulated with the Eulerian mesh.

To address computational accuracy concerns and the mode of operation, we computed a near-surface explosion 20 m above the water

surface with two different methods, the pure Eulerian mode and the standard ALE mode. In both cases, the maximum radial zone size was limited to 0.5 m. The Eulerian mesh was polar with a horizontal line defining the air-water interface such as shown in Fig. 1. Thus the interface line cut across many mixed zones. The ALE mesh, on the other hand, was a rectilinear Cartesian mesh in the water region coupled to a polar mesh describing the source and the ambient atmosphere. The air-water interface in this ALE mesh was a Lagrangian boundary with no mixed zones. We found that the wave front in the water in the Eulerian mesh was more dispersed and broad; thus the peak pressure was reduced. This implies the loss of high-frequency components of the wave. However, there was only a 2% difference in the coupled energy in the water between the two simulations.

The standard ALE mode and the Eulerian mode calculate energy coupling equally well, but to determine the wave profile or the wave spectrum close to the source, the ALE mode is superior. Because our main concern is the long wavelength components, these differences are of minor consequence. If the Eulerian mode is required, the mesh should be configured to eliminate mixed zones along the air-water interface and it should have fine zones throughout the water.

We now compare 1-kt and 10-kt explosions. Figure 4 shows isobaric contours for six calculations. A 1-kt source was placed at DOBs of 100, 20 and 10 m, with the 10-kt source at the corresponding scaled DOBs, 215, 43 and 21.5 m, respectively. The 1-kt calculations ran for 150 msec, and the 10-kt calculations ran for the equal scaled time of 323 msec. The contour of the wave front appears to scale by the cube root of the yield. The shock pressure, P_{sh}, was determined by the calculated pressure minus the overburden pressure. The peak P_{sh} of the 1-kt explosion for each DOB agrees within a few per cent with the peak P_{sh} of the 10-kt explosion for the same scaled DOB. Figure 5 shows the vertical wave profile directly under the source for each plot of Fig. 4. Interference from the surface rarefaction wave is observable for the shallower explosions, whereas the deepest explosions are unperturbed by the rarefaction wave.

We integrated the downward-directed kinetic energy coupled in the water for all the calculations we completed. Figure 6 shows the downward kinetic energy divided by yield plotted against the initial DOB. The circles represent 1-kt explosions while the squares are for 10-kt explosions. The DOB of the 10-kt explosion was scaled back to 1-kt by the cube root of the yield to make this comparison. This figure implies the following:

1. The energy coupling efficiency increases with depth, and the underwater explosion of 1 kt makes the maximum coupling at about a 20-m DOB. The maximum coupled kinetic energy in the downward directed motion is less than 15% of the yield.

2. As the source is lifted above the water, the coupling efficiency

rapidly decreases with height. At about 40 m above the surface, the coupling efficiency decreases by three orders of magnitude from the maximum coupling case.

3. Cube-root scaling applies well for the coupling efficiency. In general, scaling is not expected to be perfect due to the fact that the gravitational constant and geographical distances, such as water column depth or clear acoustic paths along the earth's surface, cannot be scaled.

Conclusion

We completed 13 simulations of 1-kt and 10-kt explosions with DOB ranging from 5 m to 323 m and HOB from 0 to 43 m. To calculate the wave profile or the source spectrum accurately, the ALE (nearly Lagrangian) mode is preferred over the Eulerian mode. However, the Eulerian mode does suffice to study the effects on low frequency signals which propagate a long distance and thus are of primary interest. The 1-kt source achieves its maximum coupling of energy at about a 20 m depth, and the maximum downward kinetic energy is less than 15% of the yield. Cube-root scaling applies reasonably well for this system.

For some cases, the computed signals reached a depth of more than 700 m, approaching the SOFAR channel. Next we will link the CALE output to the NPE code and then study the long-distance propagation of these signals.

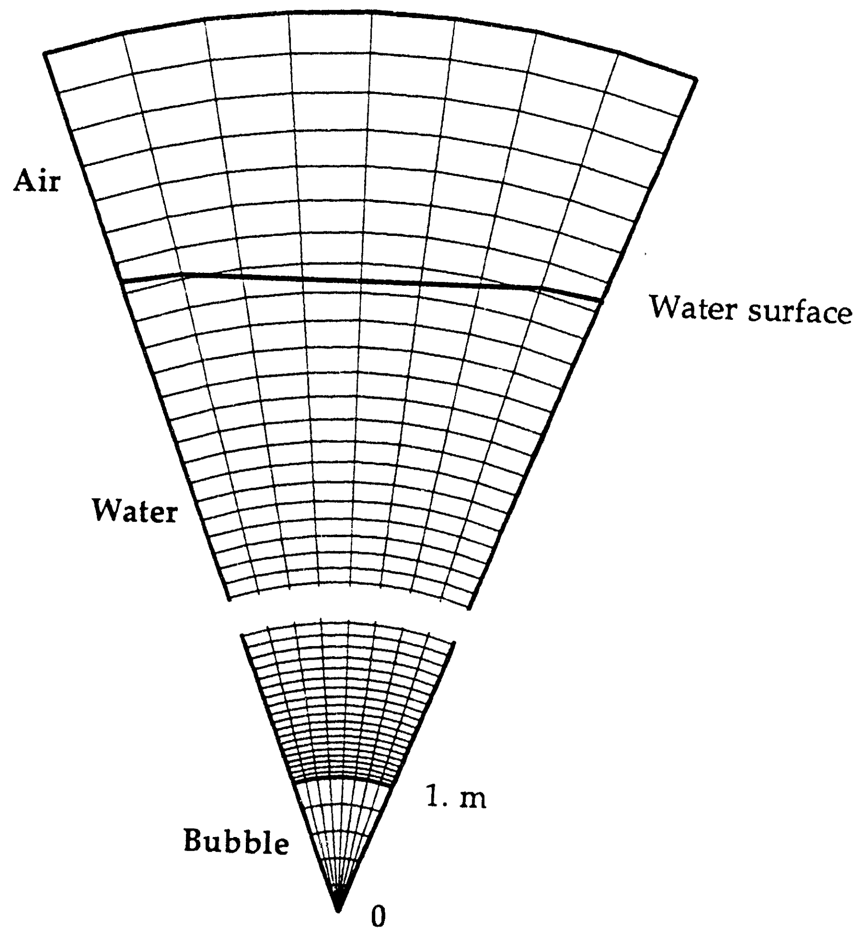

Fig. 1 Schematic partial view of a simulation in polar mesh for a 1-kt underwater explosion.

Angular resolution is 5°. There are five radial zones in the bubble, and radial zoning in water geometrically increases from 0.1 m at the gas–water interface to 0.5 m and then maintains equal zoning of 0.5 m. The horizontal line shows the water surface

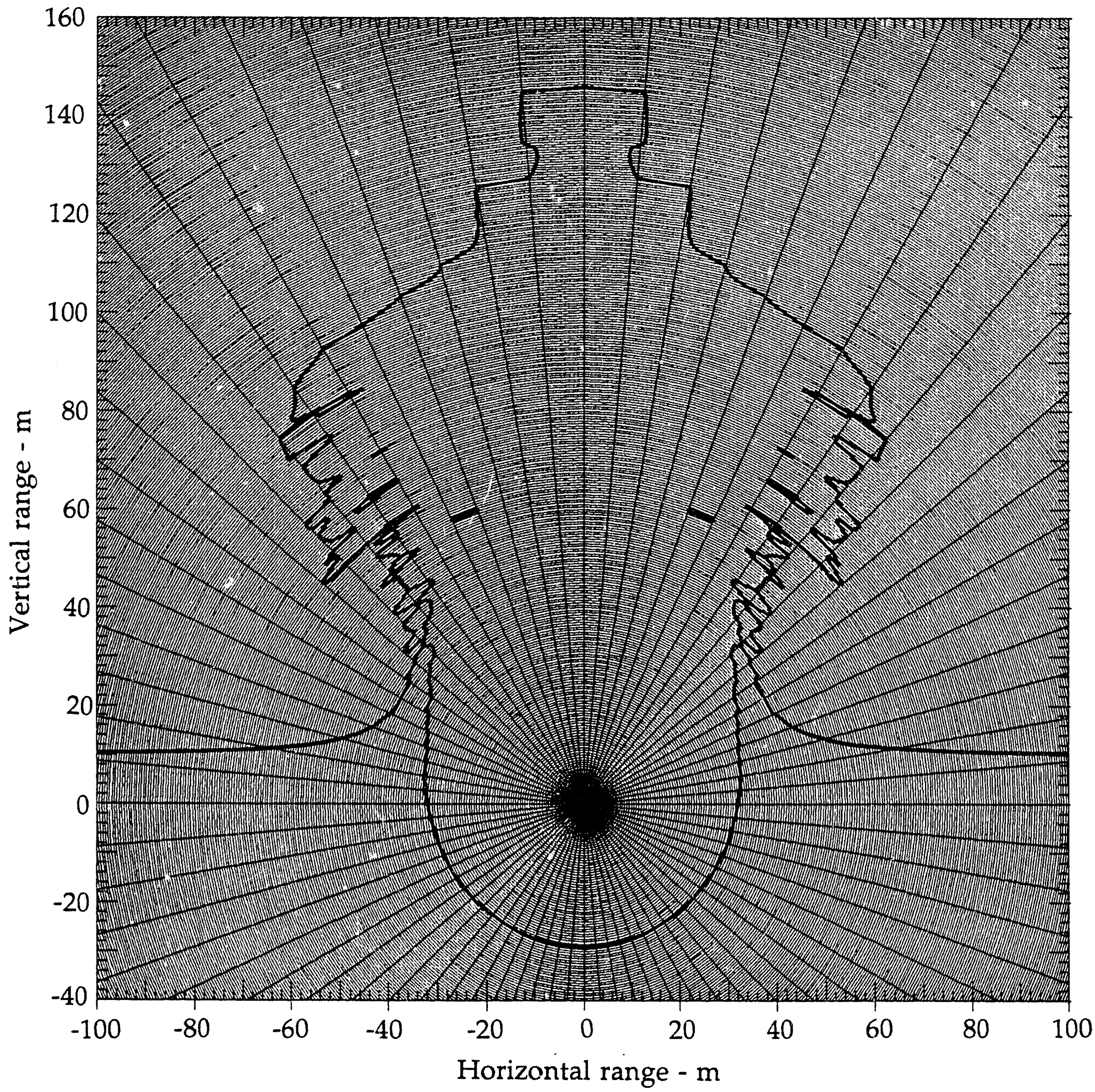

Fig. 2 1-kt underwater explosion at 150 msec (DOB 10 m).
Simulation was made with an Eulerian mesh. The bubble has broken through the water surface, and more than half of the bubble is above the water.

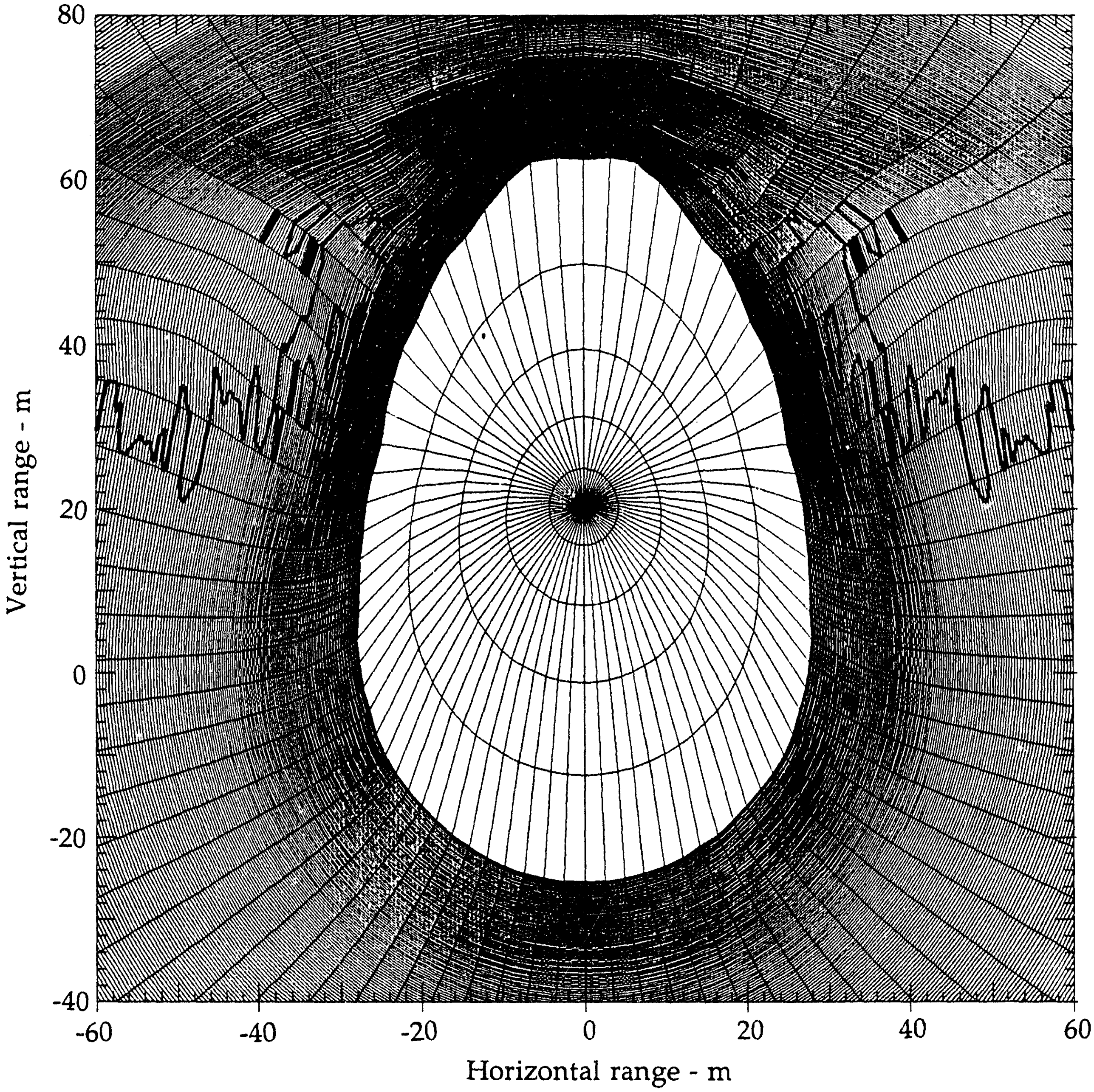

Fig. 3 1-kt underwater explosion at 150 ms (DOB 20 m).
Simulation was made with an ALE (nearly Lagrangian) mesh. The bubble boundary is a Lagrangian boundary. The bubble has penetrated the surface.

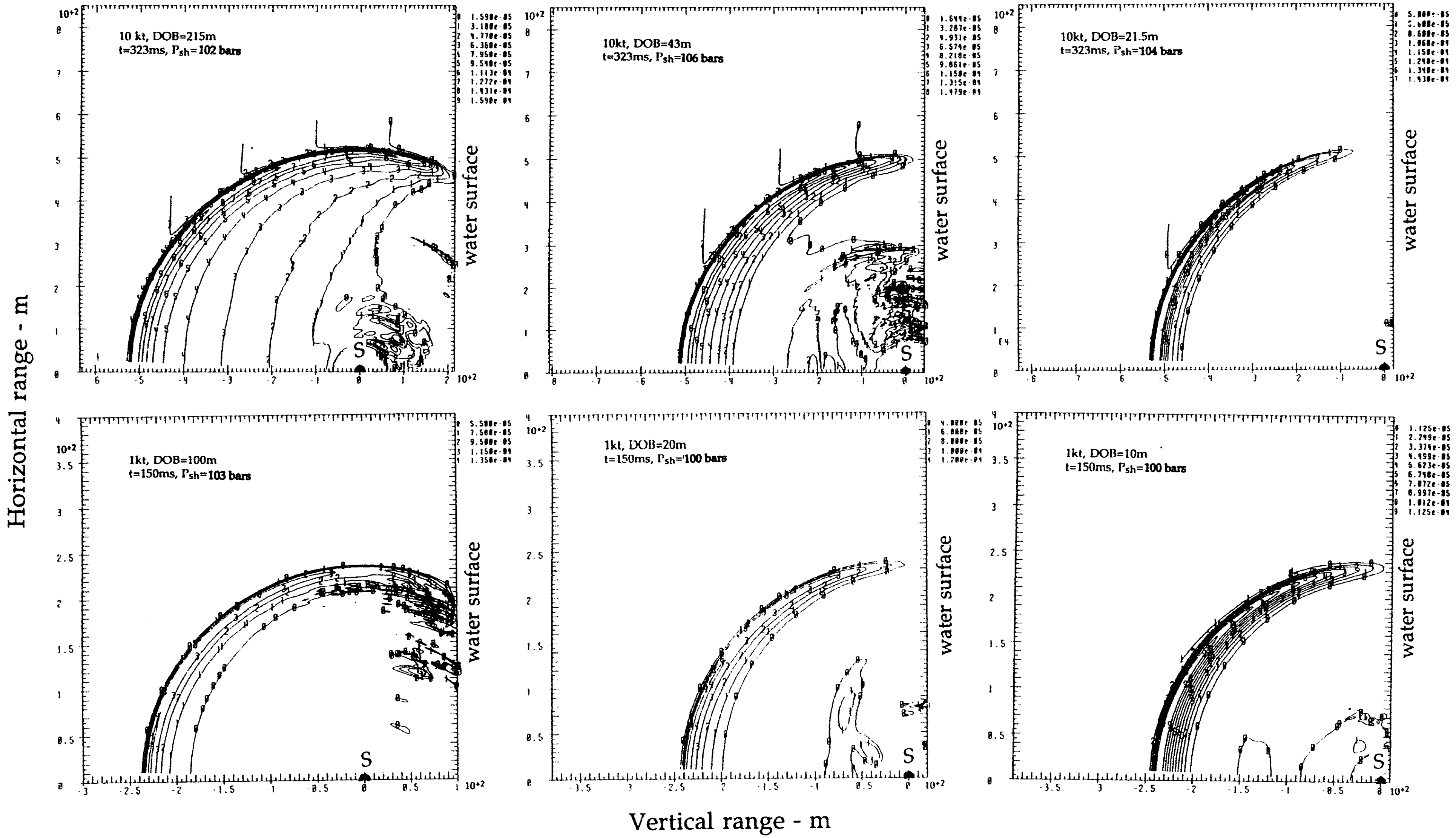

Fig. 4 Comparison of isobaric contours for 1-kt explosion to 10-kt explosion at the equivalent scaled time.

Shock pressure is the wave pressure minus the ambient pressure.

The energy source, S, was initially at the origin.

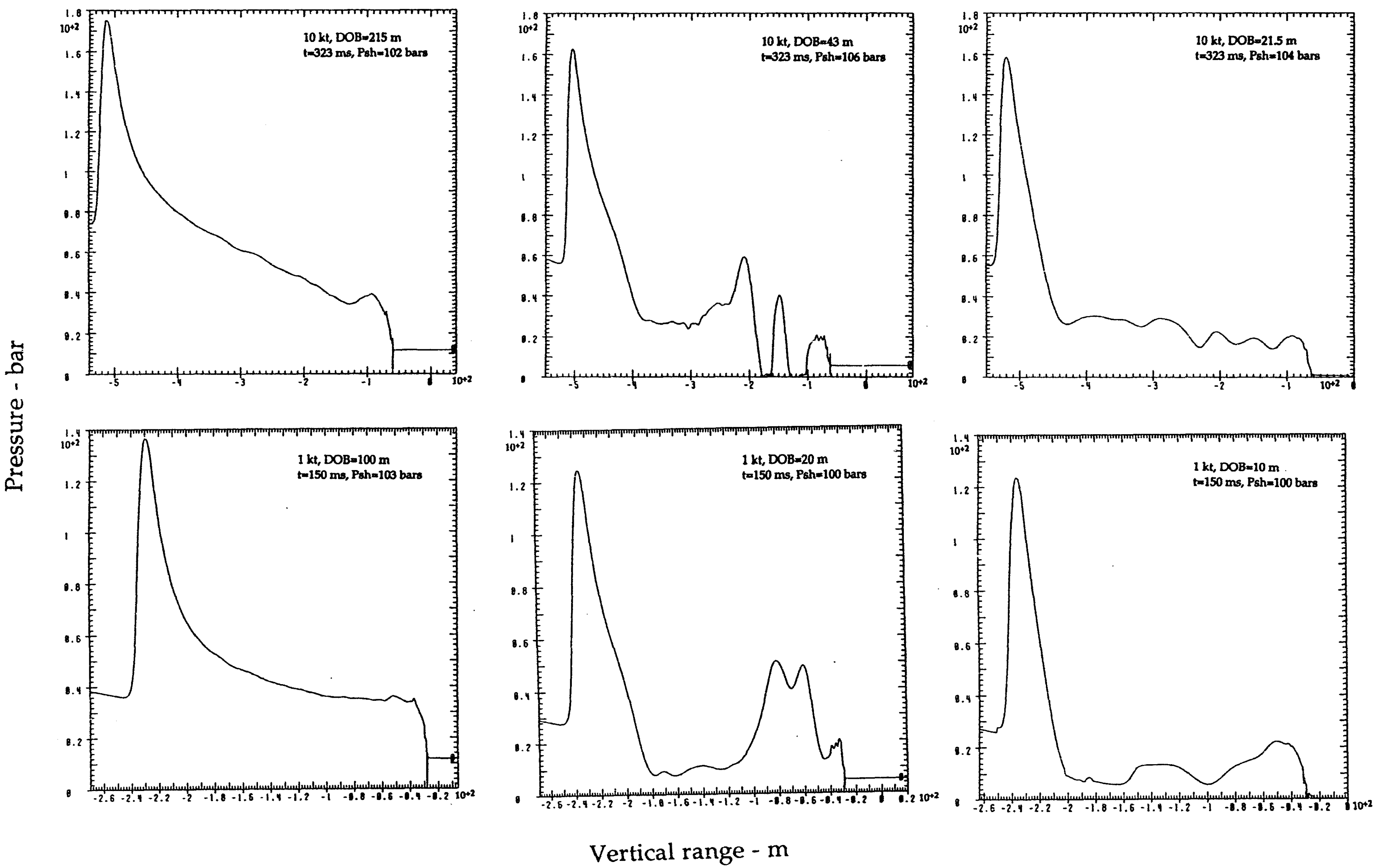

Fig. 5 Downward vertical wave profiles below the source point taken from the contour plots shown in Fig. 4. Shock pressure, Psh, is the peak pressure minus the ambient pressure.

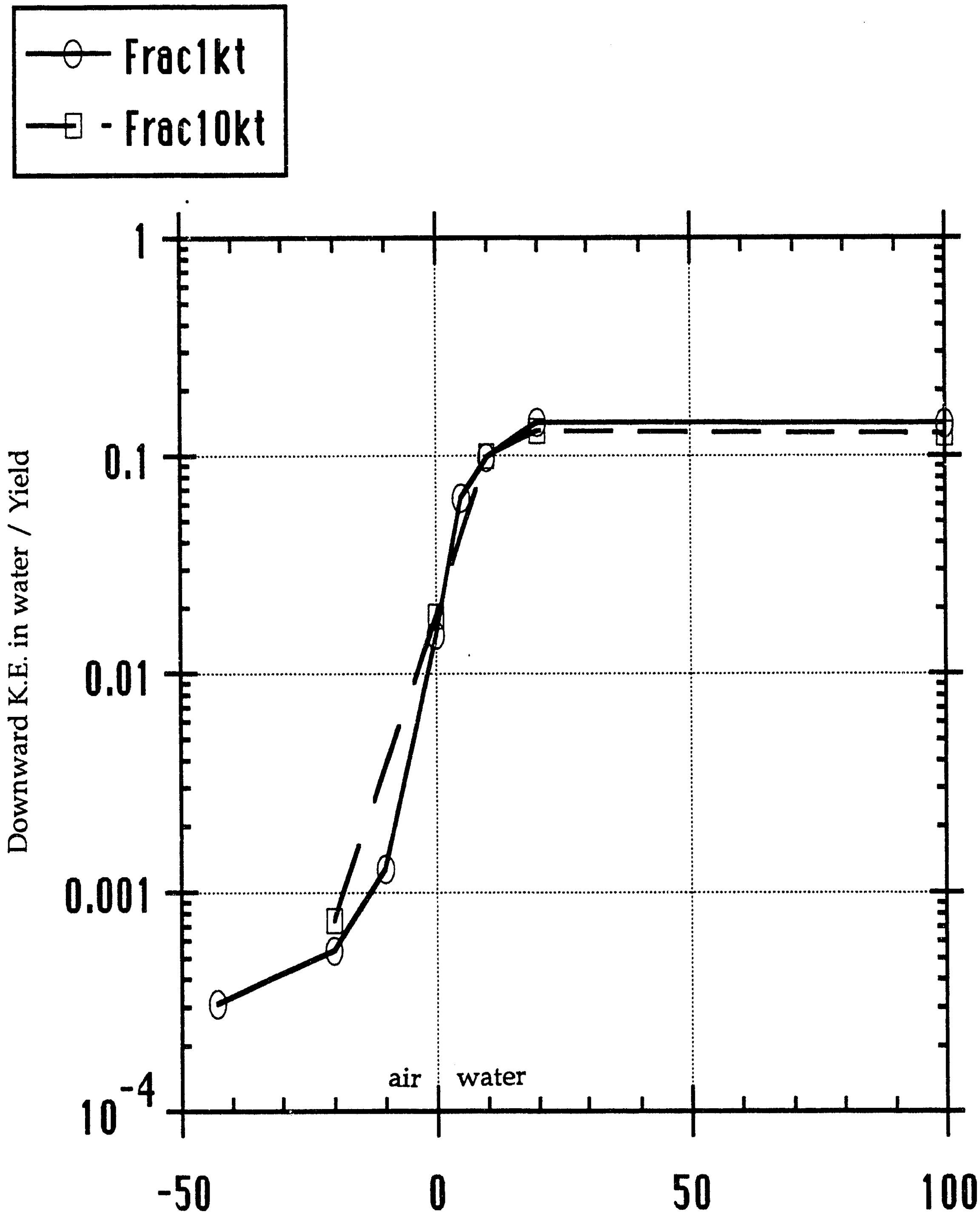

Fig. 6 Downward kinetic energy coupled in water for 1-kt and 10-kt explosions. The maximum coupling is achieved at a depth of 20 m in scaled range. The maximum downward kinetic energy is about 15% of the yield.

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